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2-IN-1 LARGE-APERTURE NB_3SN QUADRUPOLES FOR THE LHC IR

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Abstract - Double-aperture Nb_3Sn quadrupole magnets with cold and warm iron yokes and with asymmetric coils were studied for the dipole-first upgrade scenario of the LHC Interaction Regions (IR). This paper describes magnet design concepts and discusses their major performance parameters, including field gradient and field quality.

INTRODUCTION

After LHC explore physics at nominal parameters, it will be necessary to upgrade it to higher luminosity. Replacement of the low-beta insertions with higher performance design based on advanced superconducting magnets is one of the most straightforward steps in this direction. An interesting option for a new IR design is a double bore inner triplet with separation dipoles placed in front of the focusing quadrupoles [1]. This approach reduces the number of parasitic collisions by more than a factor of three with respect to the present quadrupole-first option and allows independent field error correction for each beam. However, the β_{max} is considerably larger in this layout for the same β^*. This requires using focusing quadrupoles with largest possible aperture in 2-in-1 configuration with LHC beam spacing. Preliminary analysis showed [1] that for Nb_3Sn quadrupoles at the present nominal field gradient of 205 T/m and 20% critical current margin the maximum aperture based on spacing limitations is 100 mm.

The goal of this work was to study possibilities and limitations of 2-in-1 quadrupoles with the 100 mm aperture and the nominal field gradient of 205 T/m and ~20% margin, compatible with the horizontal LHC beam position and separation distance of 194 mm. The magnet has to provide focusing-defocusing functions with respect to two counter-rotating beams as in the present LHC IR optics. Due to close location of two high-gradient large-aperture quadrupoles in these magnets, it is impossible to shield the coils from each other magnetically the way it is normally done in quadrupole designs with smaller aperture with respect to beam spacing [2]. Thus, obtaining a reasonably good field quality in 2-in1 magnet with 100 mm aperture was an important part of the study.

MAGNET DESIGNS

Two different design concepts were considered: one with remote “warm” iron yoke and another one with closer “cold” iron yoke. Both designs were based on four-layer coils with the same cables made of Nb_3Sn conductor, graded in the two outermost layers [3]. The cable and strand parameters are reported in Table 1.

To maximize the magnet efficiency, the coils were graded between two inner and two outer layers in both designs. The two innermost layers use keystoned Rutherford-type cable made of 22 1-mm Nb_3Sn strand and the two other layers use the cable made of 18 1-mm strands. This way of grading was chosen instead of the more traditional approach of using different strand sizes in the inner and outer layers but the same cable width in order to minimize the coil thickness that was critical for providing the maximum aperture size at the fixed beam separation distance.

Table 1: Cable parameters.

Parameter	Unit	Layers	
		Inner	Outer
Number of strands		22	18
Strand diameter	mm	1.000	
Cable inner thickness (bare)	mm	1.656	1.679
Cable outer thickness (bare)	mm	1.910	1.886
Cable width (bare)	mm	11.183	9.138
Cabling angle	deg	14.5	
Copper to non-copper ratio		1.2	
Insulation thickness	mm	0.18	

Warm yoke design

In the warm yoke design, the coils were placed inside a relatively thin common cylindrical iron yoke. The magnetic coupling between the coils and yoke asymmetry with respect to each coil require introducing an appropriate asymmetry into the coil geometry to obtain a good geometrical field quality.

The coil cross-sections were first optimized with constant magnetic permeability (μ=1000) and some initial yoke inner radius using the analytical solver of ROXIE code [4]. Then the yoke outer radius was optimized by the BEM-FEM solver of ROXIE code with the fixed coil geometry and the yoke inner radius using the real B-H curve in order to keep the yoke saturation effect at an acceptable level while minimizing the yoke outer radius. These steps were iteratively repeated until the satisfactory coil and yoke cross-sections were obtained. Fig. 1 shows the optimized coil cross-section having the asymmetry of quadrant coils with respect to the pole planes and different number of turns in the inner (49) and outer (61) quadrant coils.

Fig.2 presents the optimized yoke cross-section with the inner radius of 315 mm and the outer radius of 400 mm. In order to keep the iron saturation effect at an acceptable level in the operation field range, the yoke had to be distanced from the coils by about 125 mm. This space is sufficient for the strong coil support structure and cryostat components including thermal shield, cold-mass supports and vacuum vessel.

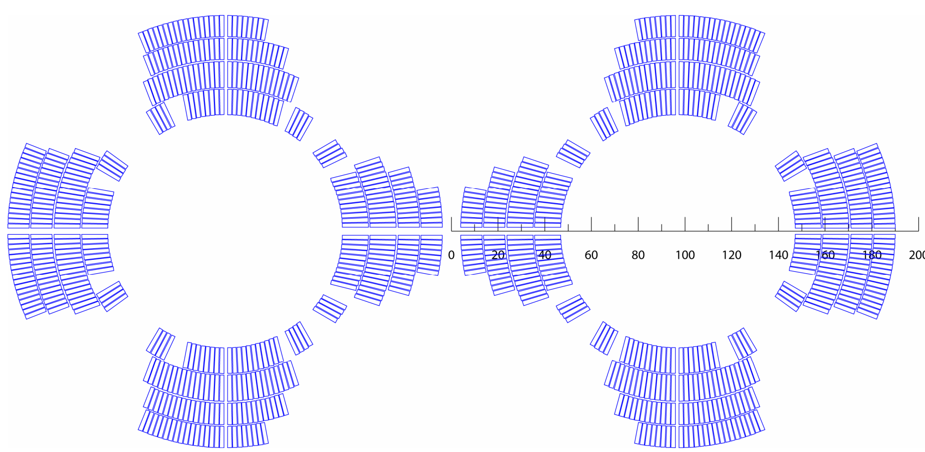

Figure 1: Coil cross-section.

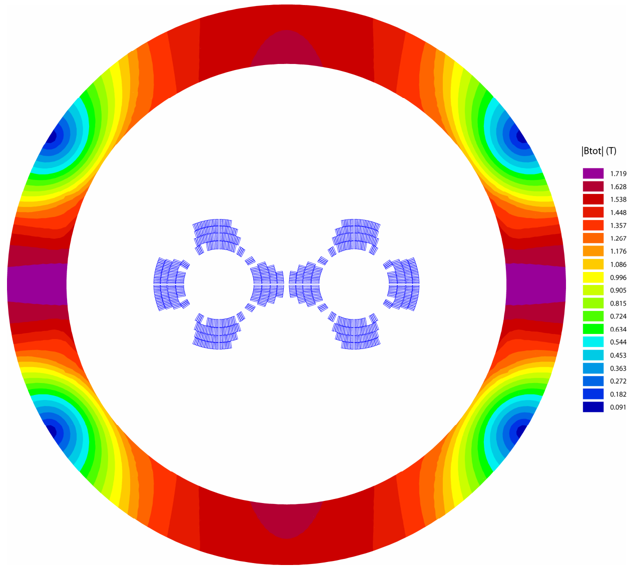

Figure 2: Magnet cross-section with magnetic flux density in the yoke at 14 kA current (G = 226.0 T/m).

Cold yoke design

In the cold yoke design, the iron yoke is closer to the coils than in the warm yoke design. Due to a complicated yoke shape required to bring the yoke closer to the coils, there was no analytical solution available at low fields. Unlike to the warm yoke design, the coil and yoke cross-sections were simultaneously optimized for a good geometrical field quality and low yoke saturation effect using the BEM-FEM solver of ROXIE code.

The optimized coil and yoke cross-sections are shown in Fig. 3 and Fig. 4. The optimum yoke outer radius is 381.22 mm. Due to the small distance between the coils, it was not possible to shield them magnetically from each other. As a result, even in the cold yoke design the coil has to be asymmetric. Although the level of asymmetry and the difference in the number of turns for the inner (53) and outer (62) quadrant coils necessary to obtain a good geometrical field quality are smaller than in the warm yoke design due to the partial shielding of the coils by closer iron yoke.

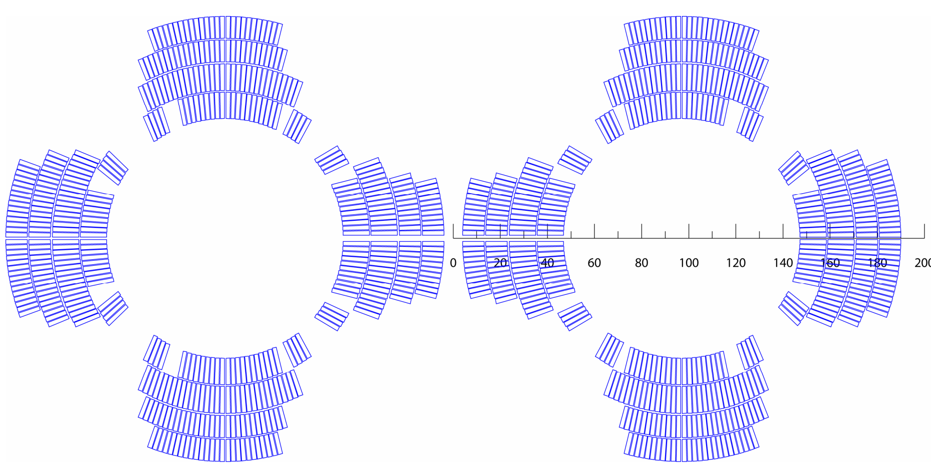

Figure 3: Coil cross-section.

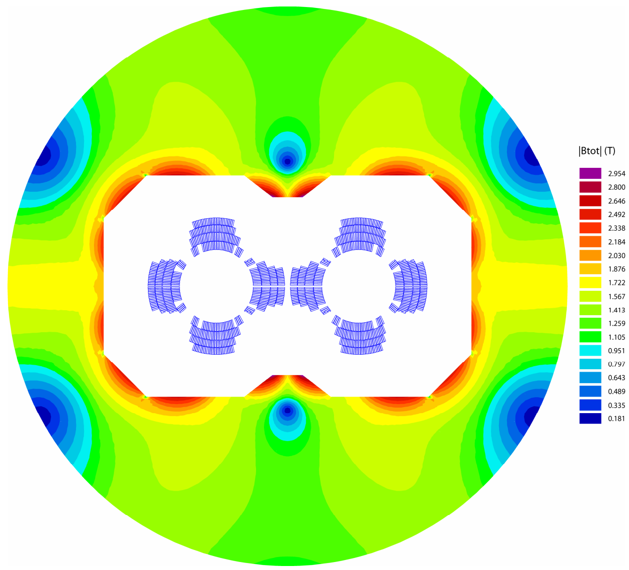

Figure 4: Magnet cross-section with magnetic flux density in the yoke at 14 kA current (G = 240.4 T/m).

MAGNET PARAMETERS

Calculated design parameters of the double-aperture quadrupoles with warm and cold iron yoke, described above, are summarized in Table 2. The performance parameters for the two designs are very close. In both cases, the target field gradient of 205 T/m with ~20% margin was achieved at a moderate critical current density in the coil of 2500 A/mm^2 and quite large Cu/nonCu ratio.

Table 2: Magnet parameters.

Parameter		Unit	Warm yoke	Cold yoke
Aperture diameter		mm	100	
Number of turns/aperture			220	230
Conductor area/aperture		cm^2	71.65	74.96
Quench gradient*		T/m	243.6	247.2
Quench current*		kA	15.10	14.40
Peak field in the coil*		T	14.1	14.3
Transfer function**		T/m/kA	16.14	17.17
Inductance/aperture**		mH/m	10.85	12.16
Stored energy/aperture**		kJ/m	875.5	866.4
Lorentz forces/ 1st octant**	F_x	MN/m	1.78	1.96
	F_y	MN/m	-3.36	-3.21

* At 1.9 K for the J_{non-Cu}(12T,4.2K) = 2500A/mm^2

** At the nominal gradient G=205 T/m

In spite of the coil asymmetry, the Lorentz forces acting on different coil octants are practically symmetric since the magnetic field conforms to the quadrupole symmetry with a high degree of accuracy.

Fig. 5 shows the quench gradient at 1.9 K as a function of the critical current density in the coil for both magnet designs.

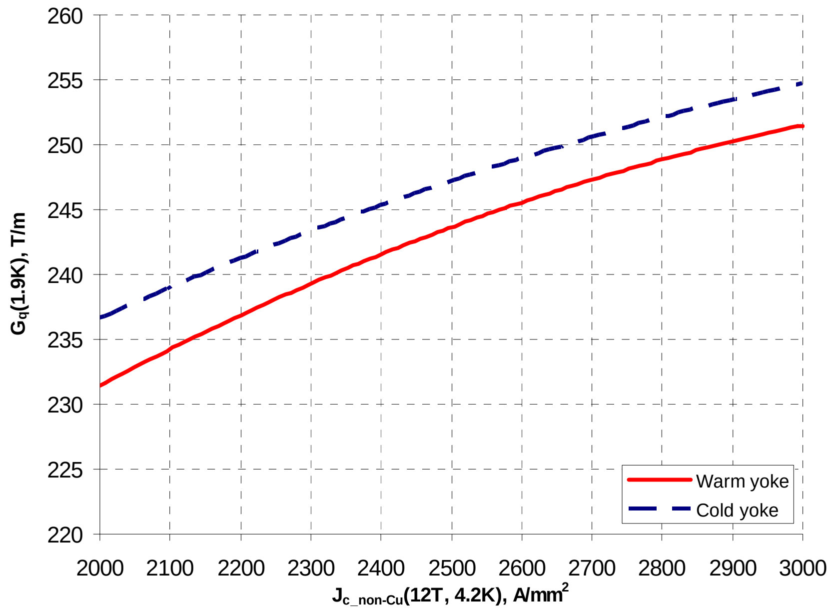

Figure 5: Quench gradient at 1.9 K.

Calculated field harmonics in the warm and cold yoke designs are reported in Table 3 at the reference radius of 25 mm. The whole spectrum of normal harmonics is allowed in both designs due to the coil and yoke asymmetry. The low-order harmonics were effectively reduced using only one wedge in each coil octant and thin midplane shims as presented in Table 3. However, the high-order harmonics are quite large in both designs.

Table 3: Geometrical harmonics at 25 mm radius, 10^{-4}.

Harmonic	IRQ design	
	Warm yoke	Cold yoke
b1	0.0002	-0.0005
b3	0.0001	0.0005
b4	0.0001	0.0042
b5	-0.0070	-0.0049
b6	0.0014	-0.0305
b7	0.0130	-0.0151
b8	-0.0013	0.0996
b9	-0.1016	0.0212
b10	0.1797	0.3404

Fig. 6 shows the yoke saturation effect in the low order harmonics for the two designs. The variation of the dipole component in both designs is within $0.2\cdot10^{-4}$ units for the field gradients up to 205 T/m. Variations of the sextupole and higher order harmonics are negligibly small in the relevant gradient range.

Since the yoke in the cold yoke design is closer to the coils than in the warm yoke design, it affects a larger number of geometrical harmonics. It could provide extra flexibility in tuning the geometrical field quality in the cold yoke design. However, the strong yoke saturation effect could primarily be alleviated only by optimizing the yoke inner surface that excluded the possibility of tuning the geometrical field quality using the yoke shape. Thus, the low order harmonics in Table 2 are comparable to the warm yoke design, while the high order harmonics are larger that reflects the added complexity of simultaneous optimization the geometrical field quality and the yoke saturation effect.

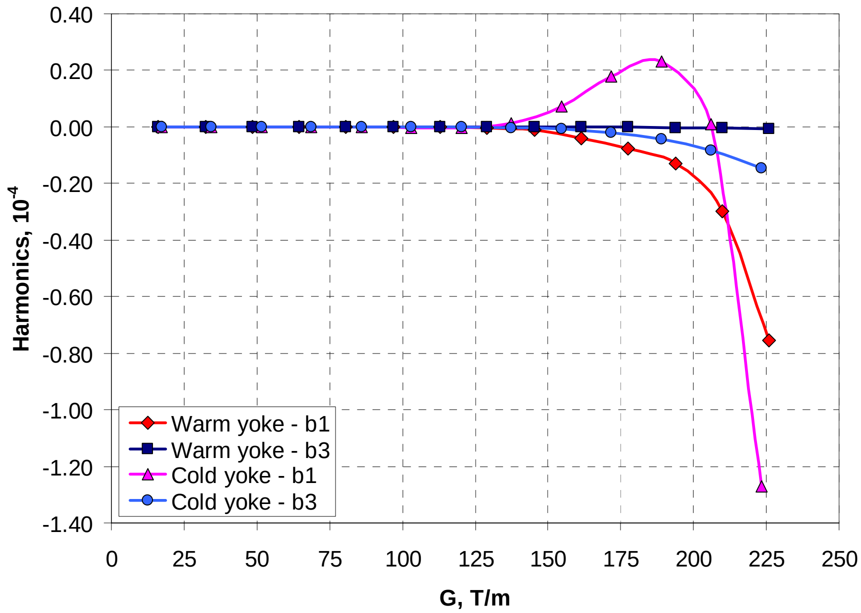

Figure 6: Yoke saturation effect.

SUMMARY

The 2-in-1 quadrupoles with 100 mm aperture suitable for the dipole-first upgrade scenario of the LHC IR region have been studied. Two possible magnet designs based on the warm and cold iron yokes were developed and analyzed. It was shown that these designs have very similar parameters and can provide the nominal field gradient and a necessary operation margin using the coils made of Nb_3Sn superconductor. The required field quality determined by the large beta-function can be achieved using the asymmetric coils.

Next steps:

- try two-three spacers in the warm yoke design to minimize the high-order harmonics (if possible then repeat it for the cold yoke design)
- check if the reduction of the critical current margin can be compensated by the higher Jc (coil volume is fixed by spacing)
- check if the best field quality provides sufficient dynamic aperture for the beam with the expected beta-max.

REFERENCES

[1] J.B. Strait, et al., “Towards a New LHC Interaction Region Design for a Luminosity Upgrade”, Proc. 2003 Particle Accelerator Conference, pp.42-44.
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[4] S. Russenchuck, “A Computer Program for the Design of Superconducting Accelerator Magnets”, CERN AT/95-39, LHC Note 354, Sept. 26, 1995.